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# AGENT TECHNOLOGY: FEASIBILITY FOR BUSINESS AND MANUFACTURING APPLICATIONS

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## FOREWORD

Electronic commerce (e-commerce) may be defined as a set of processes that support business transaction activities electronically over a network and involve information exchange, processing, and analysis. These activities spawn product information and display events, services, providers, consumers, advertisers, support for transactions, brokering systems for a variety of services and actions (e.g., finding certain products, finding cheaply priced products, etc.) The potential of agent-based systems has not been realized yet, in part, because of the lack of understanding how the agent technology supports business-to-business (b2b) e-commerce processes. This document reports our findings in investigating the current state of agent technology and the feasibility of applying agent-based computing to b2b e-commerce.

## EXECUTIVE SUMMARY

Agent-based computing is poised to emerge as the next wave in the software development paradigm. Unfortunately, there is currently no consensus on the definition of software agents. Some emphasize the intelligent nature of software agents, others suggest that any piece of software or object that can perform a specific given task is an agent. Regardless, the potential benefits of adopting an agent-based approach is to improve the business process and add value in conducting business-to-business electronic commerce over the Internet. However, application of agents and the technical difficulties associated with developing such systems needs to be investigated.

The purpose for investigating agent technology is to determine how agents can improve business-to-business (b2b) e-commerce. It was also done to provide technical assistance to the NIST Internet Commerce for Manufacturing (ICM) project in the analysis, design, and development of web-based agent technology for improving supply-chain operations in Printed Circuit Board and Printed Circuit Assembly (PCB/PCA) manufacturing.

The ICM project is a multi-disciplinary effort by the National Institute of Standards and Technology (NIST) involving the Electronics and Electrical Engineering Laboratory (EEEL), Manufacturing Engineering Laboratory (MEL), Manufacturing Extension Partnership (MEP), and Information Technology Laboratory (ITL) organizations at

NIST. The scope of work includes identifying, integrating, and evaluating existing and emerging standards and standards-based tools as part of a national testbed supporting electronic commerce in the manufacturing of printed circuit assemblies (PCA) and printed circuit boards (PCB). An ICM objective is to work with industry to create an environment where small manufacturers of mechanical and electronic components may participate competitively in virtual enterprises that manufacture printed circuit assemblies. An ICM testbed was established to test, evaluate, and demonstrate advanced technologies and standards, particularly web-based solutions, which may enhance business and manufacturing processes.

One task of the ICM project was to investigate the potential benefits of adopting an agent-based approach to conducting business-to-business electronic commerce over the Internet, and explore the business and technical issues associated with developing such systems.

This report assesses the value of agent-based technologies in business and manufacturing applications, with a special focus on the PCB and PCA industry. The analysis provides an understanding of agent technologies; evaluates current research and standards efforts; determines the extent of current applications; gauges strengths, weaknesses, opportunities, and threats; describes a prototype application of agent technologies; and concludes with an assessment of its business values and recommendations for further investigation.

This investigation concluded that agent-based computing could save steps that are currently done by humans, which has the potential of saving processing time and providing subsequent reductions in cost. The application of agent technology also points at the potential for reduction of human operating errors, thus improving the quality of the overall system. Clear quantification of the value proposition for saving steps, saving costs, and improving quality involves more research. However, based upon this investigation, it appears that agent-based computing could provide a desirable capability for flexible automation of production information retrieval and supply chain information integration.


## ACKNOWLEDGEMENT

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# 1. INTRODUCTION

Original Equipment Manufacturers (OEMs) and their supply chains must be able to share information for the purpose of completing a multitude of business activities. Information sharing among supply-chain partners continues to be carried out through a combination of meetings, electronic means, fax, and phone, all contributing to inefficient performance. The pace of current technology development, and market trends and dynamics are driving many businesses to reevaluate their processes and systems, and initiate projects that will optimize the use of technology for the purpose of cutting costs, gaining efficiencies, and expanding operations. The objective: improve the value of the company's product to its customers. To fully realize these benefits, issues of technology standards and the value of certain emerging technologies must be addressed.

At the National Institute of Standards and Technology (NIST), the Internet Commerce for Manufacturing (ICM) project is working with printed circuit board (PCB) and printed circuit assembly (PCA) manufacturers to promote the development of emerging Internet-based technologies and standards that will improve manufacturing operations and business relationships.

As part of this overall effort, a task of the ICM project is focusing on the development of emerging "Agent" technologies and assessing their feasibility as business and manufacturing software application tools for improving supply chain performance and manufacturing processes.

## 1.1 Motivation

Both PC board manufacturing information exchange and supply chain information integration require the development of distributed information systems, which will provide interoperability between applications and connection of multiple systems that reside in different machines. The objective of this agent technology task is to make an initial assessment of whether agent-based technologies represent a promising new approach to e-commerce and distributed information systems development. The anticipated value of agent-based computing is that it would enable the effective development of systems that rely on distributed resources, where no centralized control of system behavior exists and which automate and optimize business and manufacturing operations.

## 1.2 Scope

This report starts with a brief state-of-the-art description of agent technology, in particular, addressing current research and standard efforts with agent-based computing. Next, we discuss some findings of the requirements of Small and Medium Sized Enterprises (SMEs) and assess their needs and readiness to adopt Internet technologies as part of their overall business strategy. This is important in order to evaluate the potential for deployment of agent-based computing among SMEs. We then review several examples of manufacturing systems that are built using agent-based computing and discuss the opportunities for agent deployment in the manufacturing domain. Next, an experimental agent-based implementation within the ICM test bed is described using a typical " request for quote (RFQ)" scenario between a customer (OEM) and a manufacturer (EMS or Electronics Manufacturing Service) in the PCB industry. We then conclude with recommendations for further investigation into agent technology to support e-commerce in manufacturing.

### 1.3 Approach

In examining the use of agent technology in business-to-business (b2b) electronic commerce, the following steps were taken:

- Investigate how and where agent-based computing can improve various business functions, such as procurement and supply-chain management operations;
- Identify a limited set of electronic commerce and manufacturing scenarios where agents can be effectively deployed;
- Define an initial agent prototype that is open, scalable, component-based, and distributed to support complex electronic commerce applications in PCB/PCA manufacturing;
- Design, implement and demonstrate a prototype agent-based systems for a simple and realistic scenario;
- Evaluate results and provide conclusions and recommendations.

## 2. PROFILE OF AGENT TECHNOLOGY

Agent Technology refers to software "agents," or self-contained software programs that operate largely autonomously within computing environments. Agents, like any other software, must be able to communicate with the user or application to receive instructions and provide the user with the results of its activities. Unlike standard software, an agent must be able to monitor the state of its own execution environment and make the necessary decisions to carry out its delegated tasks and achieve an intended goal.

### 2.1 Agent Technology

A useful tutorial describing agent technology can be found in [OMG99]. A more theoretical definition on agents can be found in [WOOL95, NEWE88]. However, an industry-standard definition for agent technology has not yet emerged. For the purpose of this report, agents are defined by the following characteristics:

- Agents are reusable software components that provide controlled access to shared services and resources.
- Agents are the basic building blocks for agent-based applications, and applications are organized as networks of collaborating agents.
- The behavior of each agent is constrained by policies that are set by higher-level agents within a defined agent architecture.

Agent developers can design agents to have specialized capabilities that enable them to accomplish specific tasks in a particular network or system. Examples of different types of agents can be found in agent-based application systems, some of which are described in Table 1.

**Table 1 – Agent Types**

| | |
|---|---|
| **Mobile Agents** | These agents are able to navigate around a network of computing resources to obtain and process information. Mobile agents are computational software processes capable of roaming Wide Area Networks (WANs) such as the WWW, interacting with foreign hosts, gathering information on behalf of its owners and returning to its 'home' having performed set duties. Web crawlers can be thought of as "mobile agents" obtaining information on various web pages. |
| **Deliberative or Reactive Agents** | Derived from the deliberative thinking paradigm, i.e., these agents possess an internal reasoning model and they engage in planning and negotiation to achieve coordination with other agents. In contrast, reactive agents do not have an internal model of their environment. Instead they respond to stimulus in the environment in which they are embedded. |
| **Collaborative agents** | These agents cooperate with other agents to complete tasks for their owners. Successful collaborative agents must be able to negotiate with each other in order to reach mutually acceptable agreements. |

## 2.2 Agent Properties

The notion of agent technology originated in the artificial intelligence research community during the mid 1980s when researchers began taking interest in expert systems and agent-based computing [BRAD97]. While agreement on a common standard has not yet been reached, most agree that there are some common properties that differentiate agent-based programs from conventional programs. Table 2 briefly describes the common properties.

**Table 2 – Unique Properties of Agent-based Programs**

| | |
|---|---|
| **Autonomous** | Capable of acting without direct external intervention; has some degree of control over its internal state |
| **Proactive** | Goal-oriented, purposeful; does not simply react to the environment |
| **Collaborative** | Able to coordinate with other agents to achieve a common purpose |
| **Intelligent** | Able to infer or reason |
| **Adaptive** | Capable of responding to other agents and/or its environment to some |

| | |
|---|---|
| | degree. More advanced forms of adaptation permit an agent to modify its behavior based on its experience |
| **Mobile** | Able to transport itself from one machine to another |
| **Interactive** | Communicates with the environment and other agents |

In discussing these properties it is important to note, for those familiar with "expert systems" and the current progress in agent development, that there are some fundamental differences between the two. Expert systems are typically considered goal-oriented, decision-support constructs, and therefore, differ from agent-based systems in that they cannot execute autonomously, learn, or communicate and cooperate with other agents.

### 2.3 Agent Standardization Efforts

While there is no single, formal standard for agent technology, several groups and important standards exist for agent technology. An important standard commonly used as an agent communication language (ACL) is called Knowledge and Query Management Language (KQML) [YANN98, FINI93]. A related companion standard is called the Knowledge Interchange Format (KIF) [GENE92] for agent content language, developed by Genesereth at Stanford as part of the DARPA Knowledge Sharing Effort. Although not formal standards, both KQML and KIF are widely used in agent application systems.

Since 1996, two organizations, the Foundation for Intelligent Physical Agents (FIPA) [http://www.fipa.org] and Object Management Group (OMG) [http://www.omg.org] have been working to develop and promote standardization in the area of agent interoperability.

#### 2.3.1 Foundation for Intelligent Physical Agents (FIPA)

FIPA is a non-profit organization focused on the development and promotion of agent technology standards. The 50-plus-member organization has made progress in producing a number of specifications. The FIPA Specification Repository is the area where all FIPA specifications are available according to different sets of classification. The classification consists of applications, abstract architecture, agent communications, agent management and agent message transport.

Currently, these specifications can be viewed by their life cycle status, the subject area into which they fall and the year that they were made available.

#### 2.3.2 Object Management Group (OMG)

OMG is a consortium of over 500 member organizations focused on promoting an object-oriented software paradigm for distributed network-based computing applications. The agent standardization work is being conducted by the Agent Platform Special Interest Group (PSIG) [http://www.objs.com/agent/index.html]. The agent SIG was formed from the Agent Working Group in September 2000, and now reports to the OMG Platform

Technical Committee. The group now has 2 working groups: Ontology Working Group and Mobility Working Group. They have completed a green paper [OMG00a], a glossary [OMG99a], and a white paper and roadmap report [OMG00b]. The WG also issued an Agent Technology Request for Information (RFI) [OMG99b]. The OMG Agent Platform SIG anticipates issuing a request for proposals in the future.

# 3. SMALL AND MID-SIZED ENTERPRISE (SME) NEEDS ASSESSMENT

Since agent technology is early in its development and has seen very little commercial application, quantifying its impact or potential demand within industry cannot be done directly and would require significant resources and time. However, in order to gain insight into the potential interest of SMEs (SMEs with 1 to 500 employees) in agent technology, a look at the current adoption activities among SMEs of Internet and related technologies can serve as a proxy from which to estimate their future interest.

Historically, small manufacturers do not have the resources required to transform their businesses in response to the digital economy's rapid evolution. It is anticipated that many SMEs will have difficulties in conducting a majority of their business electronically. Therefore, most SMEs can be generally characterized as late adopters of electronic commerce technologies. Given the predominant position of many SMEs in the middle or bottom of most supply chains, change is usually directed by their larger customers, such as, an OEMs and first tier suppliers. Furthermore, change usually takes place only after stringent deadlines have been set. For example, this "change from the top down" is often the case in the automotive industry. It is, therefore, most likely that the adoption of agent technology will follow this same model.

The National Institute of Standards and Technology's (NIST) Manufacturing Extension Partnership (MEP) Program has recently been studying the impact of the Internet on SMEs and the findings from their research are used here to anticipate perceived value and applicability of agent technology among SMEs [KORC01].

The overall findings of the study described in Section 3.1 were based on an analysis of twelve industries. Research focused on SMEs use of electronic systems to share information, their Internet connectivity, their use of Web sites and their perceptions regarding the overall importance of the Internet to their businesses. The following subsections provide a summary of the research and a brief assessment on the potential value of agent technology.

### 3.1 Report Findings Representing the SME Marketplace

The following sections address the use of electronic systems and the Internet in conducting business operations and the level of sophistication in integrating internal operations and connectivity with customers and suppliers. These sections also distinguish the type of firm that is actively engaged with using electronic means to improve performance. This segmentation can help direct agent technology research that would be relevant to the SMEs most likely to adopt agent technology, focusing on operations, capabilities, and market demands.

### 3.1.1 Use of Electronic Systems and the Internet

The study described in [KORC01] indicated that SMEs maintain and share information electronically across several functions and that over 60 percent of SMEs maintain one-third or more of their information in electronic form. Furthermore SMEs that reported maintaining and sharing information electronically, do so to share accounting and customer order data. The study also indicated that over 50 percent of SMEs maintain additional types of electronic information. These include inventories of supplies, bids and quotes, and order tracking information. Finally, SMEs reported that email is the most-widely-used tool for electronic information sharing followed by shared databases, the Internet, Electronic Data Interchange (EDI), Enterprise Resource Planning (ERP) and custom systems.

The study revealed that SMEs are embracing the use of the Internet as indicated by the fact that almost 90 percent of SMEs responded that they are connected to the Internet. However, only a small percentage of SMEs are using high-speed connections such as Digital Subscriber Lines (DSL), Integrated Services Digital Network (ISDN) and T1 lines to connect to the Internet. 65 percent of SMEs reported that they have a company Web site, but only 20 percent have Web sites that allow customers to place or request orders online.

SMEs revealed that a relatively important use of the Internet is for sharing and exchanging information with customers. The Internet's importance to overall business performance, sharing information within the company, and exchanging information with suppliers, ranked lower.

The electronic transferring of data and information is an increasingly important function of SMEs, but at this time reliance rests largely on independent application platforms, such as Internet browsers and email systems, that do not require selection and translation technologies to pick and interpret data. As the connection between customers and companies evolve, and most likely become more sophisticated, the role of agent technologies may become more applicable.

### 3.1.2 Level of Integration Effort

The study also took measure of what action SMEs are taking in adopting eBusiness technologies and solutions. The study categorized these firms by their level of integration efforts. For example, "progressive" firms were more likely to have an external electronic presence such as a Web site, and some of them perform electronic transactions. These firms are characterized by an increasing use of hardware such as a local area network (LAN) and/or laptops, and they are more likely to use a faster Internet connection such as DSL or ISDN. Additionally, most progressive firms have had a Web site for one to two years; however, those websites are primarily static in nature and simply provide information about the company.

"Advanced" firms can be characterized by their ability to perform electronic transactions and integrate back-office functions with their Web sites. Advanced firms were found to be more likely to use a variety of hardware and networking technologies than progressive firms, including desktops, laptops and LANs. Many advanced firms also use Electronic Date Interchange (EDI) to perform transactions, and they receive more pressure from customers than other segments to perform electronic transactions. Overall, advanced firms rated the Internet higher in importance to their businesses than other firms.

As shown in Table 1, a number of variables follow the segmentation hierarchy from disengaged to advanced. The following variables tended to be more prevalent in firms that were more eBusiness advanced: inventory available electronically; bids/quotes available electronically, use of email, use of shared databases, use of LANs and laptops, and customers who require electronic transactions.

**Table 1: Usage of Electronic Systems by SMEs' Levels of eBusiness Adoption**

| | Disengaged | Slow Adopters | Progressive | Advanced |
|---|---|---|---|---|
| Inventory Available Electronically | 36% | 54% | 61% | 78% |
| Bids/Quotes Available Electronically | 36% | 54% | 58% | 80% |
| Use of email | 0% | 46% | 61% | 83% |
| Use of Shared Databases | 9% | 23% | 42% | 59% |
| Use of LAN | 0% | 42% | 50% | 73% |
| Use of Laptops | 9% | 35% | 64% | 73% |
| Customers Require Electronic Transactions | 9% | 31% | 22% | 44% |
| Web Interactivity for Customers | N/A | N/A | 14% | 49% |
| Web Interactivity for Suppliers | N/A | N/A | 22% | 41% |

Source: NIST MEP Study of U.S. Small Manufacturers' eBusiness Needs, 2000.

Significant systems integration initiatives, such as ERP implementations and the development of LANs and WANs, have been ongoing in the commercial marketplace for a number of years. As the OEMs and large first- and second- tier suppliers have completed these activities, they have pushed integration requirements down into their supply chains. This has forced many SMEs to become proactive in undertaking initiatives involving the Internet and implementing new systems and networking technologies that link their front and back office processes and systems, thereby creating the capability to better communicate internally as well as with partners, customers, and suppliers. The optimization of these technologies is still in progress.

### 3.2 Agent Technology Needs

Large manufacturers are quickly adopting the Internet and sophisticated software systems to improve their business strategy and communications within the supply chain. However, the SMEs continually facing challenging economic conditions and handicapped by slim profit margins and limited resources will be receptive to a technology that can help them optimize their current infrastructure. Technologies that require significant investment will be held off until it is required for the purpose of maintaining the existing business base.

Extrapolating from the results of the MEP study, it can be inferred that small employee-sized SMEs (SMEs with 1 to 19 employees) and those SMEs that do not engage in any electronic activities outside the firm will not be interested in agent technology. For mid or large employee-sized SMEs (SMEs with 20 to 499 employees) and those firms that are progressive and advanced in performing electronic transactions may be willing to embrace newer technology. This is due to SMEs realizing that in order to stay competitive within the digital marketplace, it is beneficial to quickly adopt new technology that will improve customer service, reduce communications cost, and accelerate flow of information. Companies that cannot adapt fast enough to thrive in these new markets will be left behind.

Agent technology offers an approach to developing distributed intelligent manufacturing systems.

## 4. AGENT-BASED COMPUTING IN MANUFACTURING DOMAIN

Agent-based computing has shown great promise as an approach to developing distributed intelligent manufacturing systems. The immediate benefits that agent technology brings to manufacturing include interoperability of heterogeneous computer and software systems; cooperation between different manufacturing stages (design, manufacturability study, production); integration of various business activities; agile manufacturing; and human machine interfaces, to mention just a few.

The production management system used by most manufacturers today is comprised of disconnected planning and execution processes, often employing legacy software applications developed over many years, i.e., Enterprise Resource Planning (ERP), schedulers, Manufacturing Execution systems (MES), etc. Although each of these software systems performs well for its designated tasks, they are not equipped to handle complex business scenarios typically involving coordination of several applications in responding to external environment changes (price fluctuations, changes of requests from customers and suppliers, etc.) and internal execution dynamics within an enterprise (resource changes, mismatches between plan and execution, etc.).

Agent technology provides an ideal approach to addressing this problem. Agent-based computing involves constructing a set of software agents that can be quickly assembled, some of which serve as front-ends for existing legacy systems, others providing additional functionalities. Embedded with specialized expertise and using a common agent communication language and shared ontology, these agents can easily gather and share required information between different management systems and human resources, as well as with other agents, and collaborate with each other to handle complex business scenarios.

A number of projects focusing on the application of agent technology to manufacturing have been carried out at universities, research institutes, and corporations throughout the world. At this time, however, these works have mostly been confined to research labs, mainly aimed at developing prototype agent systems to demonstrate the feasibility of the new technology in solving difficult tasks in manufacturing. Although no report has been published that we are aware of on successful application of agent technology in large scale manufacturing enterprises, technologies and tools developed, experience accumulated, and lessons leaned in these research projects have paved the way for agent-based computing in real-world manufacturing applications in a near future.

In what follows, a number of successful prototype multi-agent systems addressing different aspects of intelligent manufacturing are briefly described. A comprehensive survey on the development of agent-based systems for manufacturing can be found in [SHEN99].

### 4.1 CIIMPLEX

The promise of an agent-based system for enterprise integration is demonstrated in a project by the Consortium for Intelligent Integrated Manufacturing Planning-Execution (CIIMPLEX), which is described in greater detail in [PENG98]. In this project, several multi-agent systems were developed to deal with different complex business scenarios. All agents in this system speak Knowledge Query and Manipulation Language (KQML) as the agent communication language, and are supported by a communication infrastructure called Jackal to define a common ontology. The CIIMPLEX multi-agent system consists of eight agents to handle manufacturing floor exceptions. In this application, a *monitoring agent*, with access to the Manufacturing Execution System (MES), detects a shop floor exception (e.g., a machine's processing rate decreases significantly). It sends its discovery to the *scenario coordination agent*, which, in collaboration with the front-end agent of the scheduler, analyzes the potential impact of the detected exception to the ongoing production schedule and determines remedial actions to take. If the recommended action represents a major change of the current schedule, this agent identifies appropriate management personnel for approval through the *directory agent*, and then authenticates the manager through the *authentication agent,* before issuing a schedule change to the scheduler. Inter-agent coordination is provided by two special agents: *the agent name server* which works like a white page look-up service and *the broker agent* which works like a yellow page directory service.

### 4.2 Manufacturing Agent-Based Emulation System (MABES)

Manufacturing Agent-Based Emulation System (MABES) [IVEZ99] is an open framework for design and analysis of agent-controlled discrete manufacturing systems (http://www.epm.ornl.gov/ctrc/MABES2.html). The framework was originally developed to understand the scope and impacts of transitioning from traditional to lean manufacturing operations. The autonomous agent-based approaches to controlling discrete manufacturing systems were particularly useful when both traditional and lean approaches are being utilized and analyzed. The MABES scheduling and manufacturing control structure utilizes a collection of agents, each responsible for monitoring and acting on a component of the manufacturing process. A component may be a process, such as a simple drill press; a process center, such as a collection of welding robots; or a stack, such as an inventory of preprocessed components. The agents interact to control the flow of parts through either a traditional push or a lean pull system. Within the adopted approach, the overall behavior for a manufacturing line emerges from individual behaviors of, and interaction among, distributed agents. Several coordination protocols have been identified from analysis of traditional and lean scheduling approaches and their translation into the distributed agent architecture. The agents communicate through messages, taking into account their local context – the commitments to deliver resources or complete processes, and the knowledge of expected product completions. Interesting results were obtained about system dynamics and behavior in push and pull scheduling approaches for a number of discrete manufacturing lines. The initial MABES prototype was successfully completed and delivered at the Lockheed Martin Tactical Aircraft Systems manufacturing operation in Ft. Worth, TX.

### 4.3 Agent-Based Manufacturing Architecture (ABMA)

The Agent-Based Manufacturing Architecture (ABMA) is an agent-based middleware developed by Architecture Technology Company. (http://www.atcorp.com/). This multi-agent system attempts to address the problem of exchanging model and process description information between multiple legacy applications that were not initially developed to be interoperable [BUDE98]. The ABMA agents act as a middleware to facilitate the interoperation between two legacy systems: the DAS (a distributed asynchronous scheduler) by University of Strathclyde (http://www.cs.strath.ac.uk/biography/pat/) for distributed intelligent manufacturing scheduling [BURK94]; and an multi-agent system architecture developed at Sandia National Lab (http://www.sandia.gov/). ABMA demonstrates how various types of agents collaborate to solve production scheduling problems by resolving conflicts [INTE98]. As scheduling has long been recognized as one of the most difficult management tasks in manufacturing, most of the published agent systems dealing with scheduling have employed some reasoning method (e.g., blackboard architecture) from artificial intelligence in one or more of their agents.

### 4.4 University of Calgary - MetaMorph

MetaMorph by University of Calgary (http://imsg.enme.ucalgary.ca) is an agent-based system developed to integrate product design and product manufacturing. This system provides a mechanism for immediate manufacturability assessment of a product design. As a product part is progressively designed by repeated instantiation of features, manufacturability is evaluated by resource agents for every instantiation. Design

Mediator agents and Resource Mediator agents ensure coordination among design agents and resource agents. Design agents interact with resource agents via Resource Mediators to obtain manufacturability assessments during the product design process. This process not only ensures the manufacturability of a product, but also results in incremental identification of general process plans [MATU96]. This system was further extended to include production scheduling in which the Design Mediators and Resource Mediators negotiate with each other to reach an optimal compromise that satisfied both design constraints and manufacturing constraints [MATU96, SUN99].

### 4.5 University of Toronto - TOVE Project

Another active research direction in agent technology application in manufacturing involves supply chain management. Intra-enterprise supply chain management involves integration of activities among organizational components within an enterprise (e.g., Sales Department, Parts and Supply Purchase Department, Scheduling, Production and Assembly, Warehouse, etc.). Inter-enterprise supply chain connects multiple enterprises in a supplier-customer network. Improving supply chain management will result in reduction of parts inventory and rapid response to the market to improve build to order in agile manufacturing. Building an agent system for inter-enterprise supply chain management is much more complex than that for intra-enterprise supply chain management. The TOVE system developed at University of Toronto (http://www.ie.utoronto.ca/EIL/iscm-descr.html) appears to be the first to propose organizing the supply chain as a network of cooperating, intelligent agents [FOX93]. The TOVE virtual enterprise provides the unified testbed used by the specialized agents in the system for the major supply chain functions: logistics, transportation management, order acquisition, resource management, scheduling and dispatching. These agents rely on shared ontologies for activity, state, time, resources, cost, quality and organization as a common vocabulary for communication and use the services of information agents that automatically distribute information and manage information consistency and evolution.

### 4.6 Carnegie Mellon University- Ozone Project

Recent work in supply chain management include an agent-based modeling and simulation environment for analyzing supply-chain management strategies, policies and decisions developed at Carnegie Mellon University (http://www.cs.cmu.edu/afs/cs.cmu.edu/project/ozone/www/supply-chain/supply-chain.html) [SWAM96]. In this environment models are defined in terms of constituent supply chain "agents" (e.g., suppliers, buyers, distributors), their structural relationships, interaction protocols and coordination policies, capturing the locality that typically exists with respect to the purview, operating constraints and objectives of individual supply chain entities. The agent-based approach provides flexible and rapid configuration of agent systems for alternative scenarios, allowing one to analyze the supply chain performance from a variety of organizational perspectives.

### 4.7 Fujitsu

Fujitsu Technology Laboratory has developed an agent system for Hitachi's color television production in which agents at different sites of the supply chain within Hitachi (the warehouses at distribution centers, individual assembly plants, etc.) collaborate with each other to resolve syntactical and semantic conflicts between heterogeneous databases at these sites (http://www.fujitsu.co.jp/en/).

### 4.8 GenCAM Multi-Agent System (GCMAS)

The National Institute of Standards and Technology (NIST) within the Internet Commerce for Manufacturing (ICM) project has developed a prototype multi-agent system consisting of a bidding process for printed circuit board assembly. A full description of this prototype appears in Appendix A of this report.

## 5. EVALUATION OF AGENT-BASED COMPUTING IN MANUFACTURING

In reviewing the various agent-based applications described previously, we found very limited discussion on the value proposition for deploying an agent approach versus a traditional programming approach. Performance metrics and data were typically absent to show conclusively that an agent-based system offers competitive advantages or added value. However, these systems proved that using agent-based computing does enhance large combinatorial optimization problems.

### 5.1 OPPORTUNITIES FOR AGENT DEPLOYMENT

Agent-based software systems can assist in performing a variety of computational tasks. Some of these are briefly described below:

**Searching and discovering information** – The vast amount of information over a web poses a difficult problem for most users to effectively retrieve useful information. Search agents can contain specific knowledge about the information that is being searched, while discovery agents can discover the information based upon domain knowledge. The search and discovery agents must include knowledge of the types of information available at each source, how to access that information, and other potentially useful knowledge, such as the reliability and accuracy of the information source.

**Information filtering** – Information filtering agents attempt to deal with the problem of the vast space of information by either limiting or sorting the information coming to a user. This type of agent has enough knowledge about the user's information needs so that it can select only those documents that would be of interest. These types of agents typically screen out irrelevant information, thus preventing the user from being overwhelmed by a flood of information.

**Intuitive human computer interface** – An interface agent is a program that is able to assist the user in operating and manipulating the underlying system. An interface agent is able to intercept the input to and from the user, examine it, and take appropriate action. They function as a bridge between the user and the computer systems, which may be distributed and form large, complex systems of systems. Examples include, distributed database management systems, and a web of documents in HTML or XML.

**Legacy systems interoperability** – Many legacy systems exist within the manufacturing domain. These systems are often closed and do not interoperate and interface with other legacy systems. Wrapper agents are special-purpose agent-software that can be designed and used to permit legacy systems to interact with each other in a more transparent manner.

**Negotiation, Mediation and Brokering** – Agents can be considered as middleware software that sits between two software modules and facilitate interactions between the two parties. These agents can be designed to perform the role of negotiators, mediators and brokers. For example, agents can be used in auctioning situations to optimize the grouping of items into lots that are likely to obtain the maximum profit for the auctioneer, or conversely, obtain the biggest value at the lowest cost for the buyer. Another example is using agents to automatically find supplies from supplier catalogs in which price, availability, quantity, and other factors are optimized for the buyer.

**Schedule management** – Agent applications are particularly suited for performing schedule management, monitoring, alerting and order tracking. These tasks consist of making decisions with dynamic input data. Ruled-based inference capabilities are characteristics of intelligent agent-based computing. An example is the MABES project in which a network of agents cooperated to schedule use of manufacturing equipment cells and achieve optimum production throughput on the shop floor.

## 6.0 CONCLUSIONS

Agent-based computing is best suited to environments when the rules of encounter change dynamically. Within the b2b electronic commerce for manufacturing environment, there are many scenarios where each party determines its own rules, and the parties agree to dynamically change rules during the business or manufacturing process.

Agent-based computing is best deployed in situations where decisions are automated, such as reordering goods or rescheduling of equipment. It is important to understand clearly which decisions can be entrusted to software and which decisions must be made by humans or by a combination of humans and software.

With the advent of electronic commerce on the Internet, there is potential for an intelligent search agent to sift through an overwhelming amount of information. There may be many types of business agents designed for different purposes. Most of them, at first, could do simple tasks such as searching for products or finding information on subjects of interest. Eventually, agents may become more intelligent and might possibly use inferential reasoning with a collection of knowledge stored in the form of rules. Enabling communication among agents can offer further improvement by allowing collaboration and cooperation in performing complex processing tasks that involve multiple goals, and extensive and dynamically changing information.

## 6.1 Value Proposition for the GenCAM Prototype Multi-agent System

A typical request for a quote (RFQ) process in manufacturing printed circuit assemblies and boards involves many supply-chain partners and entails many steps currently done by humans. Using e-business and agents to perform this process offers the potential of improving supply-chain integration and correspondingly, the time and cost needed to bid and manufacture the product. The agent testbed, described in Appendix A, was undertaken by the ICM project to investigate the roles and potential use of agents to assist in the Quote-Bid process in manufacturing printed circuit assemblies under an e-commerce scenario. The GenCAM standard (IPC 2511) was used to provide design information for bidding and manufacture of printed circuit assemblies and boards. For simplicity, only a single-tier supply chain, consisting of the OEM (customer) and the EMS (manufacturer) was used. However, this scenario was sufficient to investigate the role, use, and possible value of agents in this process.

The prototype RFP bidding scenario, described in Appendix A, consists of: a minimum of two round trip message exchanges between the OEM and EMS; optionally, multiple accesses to the GenCAM database, by the EMS to obtain additional product information; and, the translation and exchange of RFQ data , between the internal OEM form and the external web form received by the EMS. Using an agent-based computing approach, all of these can be done rapidly in an automatic and transparent way with minimum or no human intervention.

Depending upon the level of sophistication in an actual application, and the level of electronic commerce readiness, the agent application could save significant steps in the RFQ transactions, resulting in a reduced response time to the bid, and, subsequently, reduced costs.

The agent application scenario also has potential for a reduction in human operating errors, thus improving the quality of the overall RFQ bidding process. Finally, it may be easier to add value in the areas of evaluation or negotiation of bids simply by constructing other negotiation agents to the multi-agent system.

Clear quantification of the value proposition for saving steps, saving cost, and improving quality involves more research. However, based upon this case study, it appears that agent-based computing could provide a desirable capability for flexible production, information retrieval, and supply chain information integration.

## 6.2 Recommendations for Further Investigation

The initial feedback from participants in the manufacturing industry indicates that the agent-based approach could provide a desirable capability for flexible product information retrieval and supply chain information integration. Although preliminary, this feedback begins to validate our intuition in focusing on the two important areas for agent-based information systems: product information retrieval and supply chain information integration.

To further the understanding of agent-technology applications in manufacturing environments, several areas to pursue regarding further research are recommended.

The dominant theme of agent technology is that it offers a programming paradigm that greatly promotes reusable software components. Each special-purpose software component can be called an "agent" which performs a specific task and can interact with other agents. These agents, or reusable software components, can be collected in a library; however, the methods for providing access to and enabling the use of reusable software components needs further research. Another area of research would be to develop technologies for programming the interactions between different software components, whether those components are small or large.

Another area of potential research is "Ontology." Each agent, semantically, must understand the interlingua and domain knowledge of other agents in order to interact with them. The capability of building a community of agents that can interoperate and share knowledge is still a research topic.

We contend that, with the emergence of B2B e-commerce on the Internet, and emerging technologies and tools (e.g., XML, RDF, DAML+OIL), agent-based computing will become increasingly more attractive and practical, and evolve as a mainstream approach for distributed systems development. This study offers a preliminary view into the future of agent-based information systems development in support of distributed manufacturing enterprises.

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# APPENDIX A

## Agent-based Computing Prototype

This appendix describes a prototype multi-agent system (MAS) developed at NIST under the ICM project, to facilitate the bidding process for a printed circuit boards and assemblies (PCB/PCA). The objectives of the prototype system will be discussed. This is followed with a description of the prototype MAS scenario. Some value proposition will be assessed.

## Objectives

In an agent-based approach, a complex problem can be solved by a collection of simple, autonomous software agents, each of which is created for and called upon to perform specific functions. Agents collaborate with each other, with other applications and humans by exchanging messages at a high level of abstraction (in comparison to other paradigms such as an object-oriented approach). These and other properties of multi-agent systems make agent technology a powerful tool for creating, integrating, maintaining, and extending large, complex software systems. Adoption of agent technology in B2B e-commerce activities is thus expected to improve various functions in its business and manufacturing activities, such as procurement and supply-chain management operations.

The purpose of the prototype MAS is to demonstrate the concept and assess the added value of this approach. In particular, this manufacturing agent application is to demonstrate the value of agent technology in a request for quote bidding scenario.

## Description of GenCAM Request for Quote Scenario

The prototype multi-agent system consists of a bidding process for a printed circuit board assembly. The scenario starts with an OEM who wishes to custom-build a printed circuit board (PCB). Typically, the OEM, or customer, sends a "Request For Quote" (RFQ), via the Internet, to board manufacturers, EMSs, selected from an Approved Vendor List (AVL). The RFQ provides business and technical product information, and invites the vendors to submit bids for the board (with the required quantity and delivery date specified in the RFQ). The OEM and EMS then communicate with each other to negotiate terms of the bid (e.g., price), or to make changes needed to manufacture the product . It is often the case that the EMS needs additional technical information about the board design (e.g., the number of the holes on the board and their diameters, maximum length and width of the board, etc.) from the OEM in order to form a bid.

It is assumed that the design specification of the board is already written or partially written in a GenCAM file [GENC00]. GenCAM is a Computer-Aided Design (CAD) file specification language standardized by IPC. IPC is the electronics manufacturing industry trade and standards association [IPC01].

The agent prototype includes a GenCAM expert agent who knows how and where to access the GenCAM file and properly extract required information from the file, and send it to the EMS. The EMS sends the final bid response to the OEM. Further details on the prototype multi-agent system for the GenCAM RFQ scenario can be found in [FONG00a, FONG00b].

**Current State of RFQ Process**

Figure 1 below depicts a portion of an RFQ scenario involving GenCAM files. Humans (managers, specialists) currently do many steps listed in the Figure.

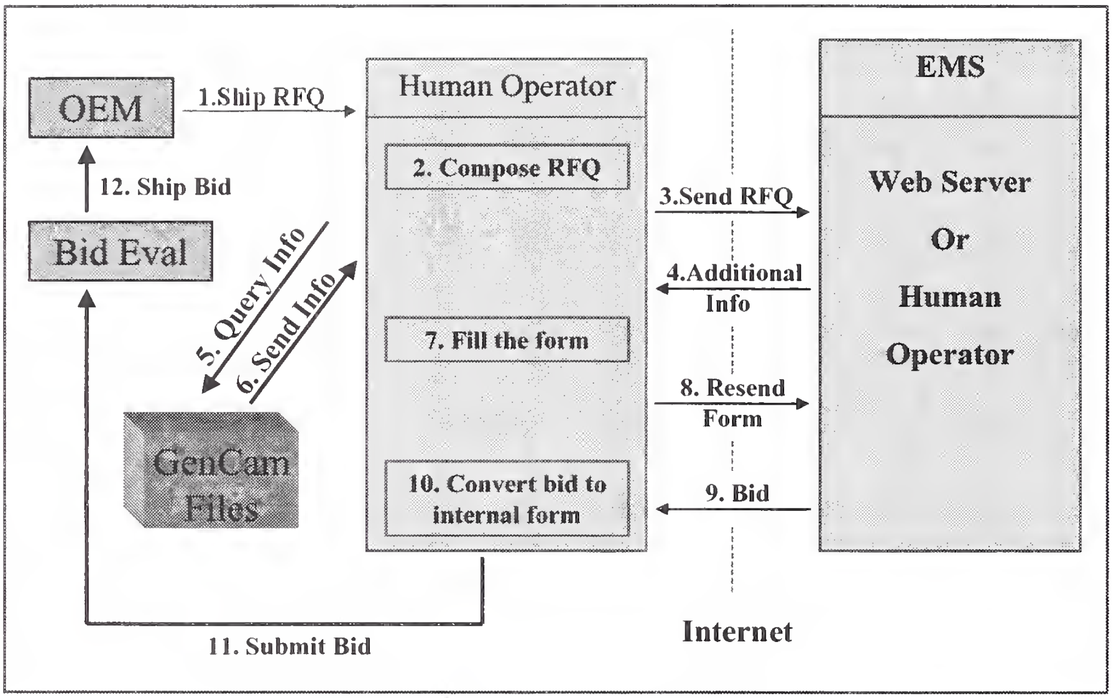


Figure 1 – The RFQ Scenario

**GenCAM Multi-Agent System**

The prototype GenCAM MAS consists of a collection of autonomous software agents implemented in variety of programming languages, each of which has its own functionality that can be used to realize some operations of the RFQ process. These agents collaborate with each other and with other resources in the system to achieve the common goal, namely to complete the entire RFQ process.

The prototype agent system for RFQ consists of two service agents and three special agents. The two service agents are:

- Agent Name Server (ANS)
- Broker Agent (BA)

and the three special agents are:

- Gateway Agent (GA)
- Web Assistant Agent (WA)

- GenCAM Specialist Agent (GCA)

All of these agents (except ANS) and their relationships to each other and external entities are depicted in Figure 2 below.

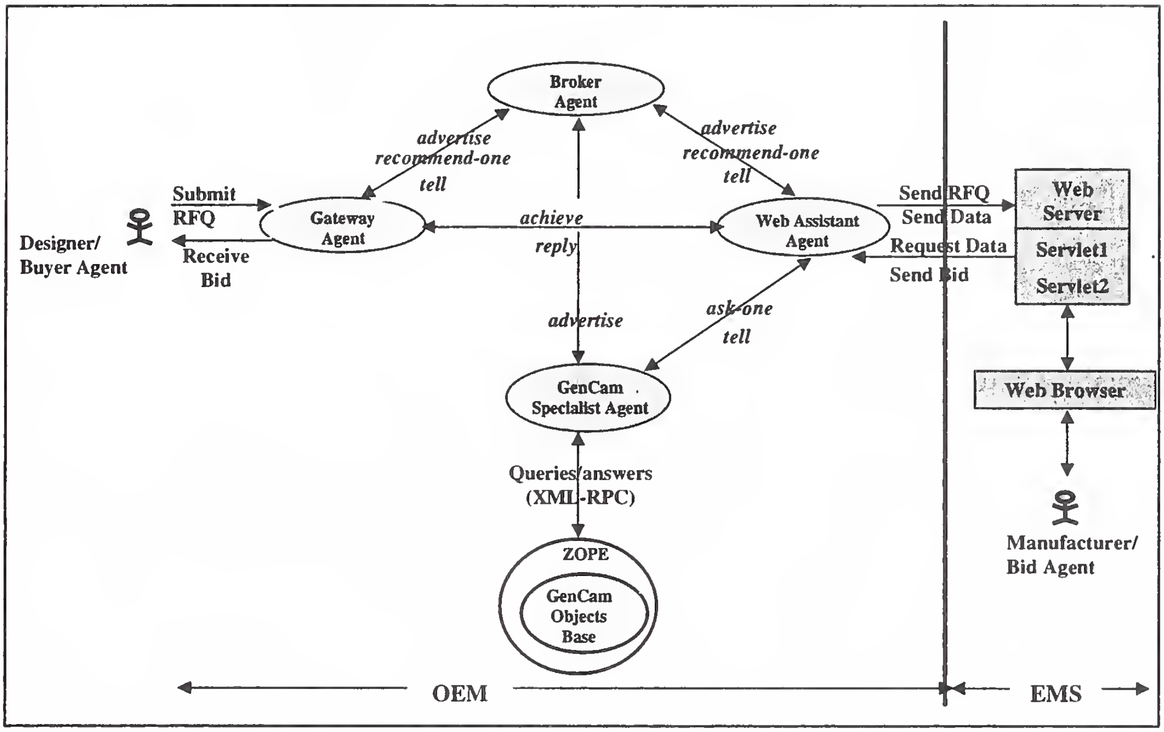


Figure 2 – GCMAS for GenCAM RFQ Scenario

The Agent Naming Service (ANS) maintains an address table of all registered agents, accessible through the agents' symbolic names. It serves as the central repository of physical addresses of all agents in the system and provides a white pages-like service. A newly created agent must register itself with the ANS with its proposed symbolic name, physical address and possibly other information.

The GA connects the agent system with the user or rest of the OEM enterprise. In particular, it does the following:

1) Receives the "Ship RFQ" from a human;
2) Converts "Ship RFQ" to the format suitable to the WA and sends it to the WA for the latter to solicit bids from EMS; and
3) Receives the final bids from individual EMSs, converts the bids to the format suitable for the OEM's consumption, and then returns them tothe OEM as a "Ship Bid."

The GA can be expanded to handle additional tasks, such as bid evaluation/selection and negotiation of terms (e.g., prices, delivery dates/quantities), or additional agents could be included to handle other tasks.

The WA attempts to automate the web operations at the OEM side when the OEM communicates with EMS during the bidding process. The implementation of the WA consists of two modules, the agent-based module and the Web-based module. The agent-based module handles all communication tasks with other agents, while the Web-based module handles the Internet communication with EMSs. The interface between the two modules may be as simple as direct function or procedure calls, especially if only one EMS and one RFQ is involved at a given time (i.e., there is only a single communication thread at a time). Otherwise, the communication may be much more complicated to handle multiple threads.

The GCA is an information retrieval agent. PCA design data is organized as a GenCAM Object Base (GCOB). A set of access methods (written in Python) is developed to query (and manipulate) these objects. In the initial implementation, the GenCAM Specialist Agent, when requested by other agents (say, WA), extracts certain GenCAM data by calling some pre-defined procedures. This agent can be expanded to handle other tasks such as processing complex, compound queries beyond simple invocations of pre-defined methods and realizing certain access control.

The GCMAS software agents communicate with each other using Knowledge Query Manipulation Language (KQML) [YANN97]. KQML was developed by the DARPA Knowledge Sharing Effort. It is intended to be a high-level language to be used by knowledge-based systems to share knowledge at run time. KQML is a language for programs to use to communicate attitudes about information, such as querying, stating, believing, subscribing, and achieving. Examples of KQML's performatives are "advertise," "recommend-one," "ask-one," "tell," etc.

Inter-agent communication in the system is supported by Jackal [PENG98], a Java-based agent communication infrastructure developed at University of Maryland Baltimore County (UMBC). Jackal provides a set of service agents to provide collaboration among the agent community with a common ontology.